EXPERIMENTAL ROUNDING OF OLIVINE FRAGMENTS IN FeNi METAL - IMPLICATIONS FOR THE THERMAL HISTORY OF STONY-IRON METEORITES. K. Saiki[1], D. Laporte[2], S. Nakashima[1] and D. Vielzeuf[2], [1]Geological Institute, Faculty of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, 113 Tokyo, Japan (psykey@geol.s.u-tokyo.ac.jp), [2]Université Blaise Pascal and CNRS, URA No10, 5 rue Kessler, F-63038, Clermont-Ferrand, France.

INTRODUCTION: Pallasites are stony-iron meteorites mainly composed of FeNi metal and olivine in approximately equal amounts, with minor phases such as troilite, FeS, and schreibersite, Fe3P [1,2]. They are presumed to be fragments of the core-mantle interface from small parent bodies (50-100 km diameter). One of the interesting features of pallasites is that olivine shows a wide range of grain shapes from angular to rounded ones [1,2]. Pallasites with angular olivines are best exemplified by Eagle Station sample, which contains irregular, often highly elongated, angular fragments with grain size in the range < 1 to 25 mm. On the other hands olivine in Brenham sample, for example, occurs either as isolated rounded grains, or more commonly as clusters characterized by rounded olivine-metal interfaces and by 120° angles at olivine triple junctions. Grain size of these rounded olivines is 5 to 15 mm. Several authors suggested that these rounded corners were the product of annealing at high temperatures in the parent body. Ohtani [3] suggested that olivine grain shapes in pallasites could be used to determine the thermal history of their parent bodies (including peak temperature and cooling rate). He modified a model developed for rounded mineral inclusions in schists and peridotites [4,5] to predict the rounding kinetics of olivine in metal. In order to provide an experimental basis for this rounding process, we conducted a series of annealing experiments of a mixture of olivine fragments and metal at high temperature.

EXPERIMENT: A fine powder of San Carlos olivine (≤20 µm) was mixed with Fe-Ni powder (Ni:10 wt%) in the volume ratio 1:5. The starting mix was loaded into a MgO capsule that was placed in a non end-loaded piston-cylinder assembly and subjected to a pressure of 1GPa and a temperature of 1200°C, 1300°C, and 1400°C from 4 hours to 7 days. The experimental charges were mounted in epoxy resin, cut lengthwise in two, and polished with 1.0 and 0.3 µm almina grit. Products were observed by reflected light microscopy and scanning electron microscopy (SEM) using secondary electron imaging. For quantitative analysis of grain shape and size, the SEM images of polished sections were stored as gray level digital images.

We succeeded in reproducing the textural features of the pallasites at a miniature scale. Figures 1 and 2 are secondary electron images of experimental products at 1400°C, 1G Pa. Gray particles are olivine and bright matrices are Fe-Ni metal. The texture after 4 hours (Fig.1) is very similar to pallasites including angular olivines such as Eagle Station. On the contrary the texture after 7 days (Fig.2) is similar to pallasites including rounded olivine such as Brenham. It should be noted that the textures of our experimental pallasites are 100 to 1000 times smaller than natural pallasites. The rounding rate is enough rapid in micrometer scale, even though our experiments were performed below the solidus of the Fe-Ni metal. ≤5 µm in diameter become nearly spherical within 7 days at 1400°C.

ESTIMATION OF ROUNDING KINETICS: In order to determine the rounding kinetics, we quantified the shape of olivine grains in our experimental products and performed a numerical simulation of the rounding process. We selected large and isolated single grains, extracted 30 points (from P_1 to P_{30}) from the grain contour and interpolated these points by a cubic parametric spline function. Once spline functions are obtained, curvature (κ) at any points on the grain corner can be calculated. Standard deviations of curvatures ($\sigma\kappa$) are also determined.

Rounded corners of crystals are thought to have been formed by the diffusion of lattice-forming atoms due to a reduction of the interfacial energy between the crystal grains and the surrounding phase. The difference in chemical potential between curved corner and flat surfaces is given by the Gibbs-Thomson equation as

$\Delta\mu = \gamma\Omega/r$, where r is radius of curvature, Ω is the volume of the atom, and γ is the interfacial energy [6].

A local volume change ΔV_j at a node P_j during Δt (time) are calculated as follows;

$$\Delta V_j = J_j w \Delta t = \frac{-D\gamma}{kTL}\left(\frac{2}{r_j} - \frac{1}{r_{j-1}} - \frac{1}{r_{j+1}}\right) w\Omega\Delta t \qquad (1)$$

Where D is effective diffusion coefficient of atoms and w is effective cross sectional area of diffusion path. All ΔV_j at each node P_j on a grain corner can be calculated. We made a rounding simulation program using this equation and calculated the change of shape step by step. By this simulation, we can estimate the volume flux during our rounding experiments. For the data of D, w and γ, there is no accurate data, therefore we tried to estimate $tDw\gamma$. We call this value as virtual time.

We picked up grain shapes from digitized secondary electron images of olivine grains in experimental products at 1G Pa. The grain shapes at 1200°C for 4 hours (group A) are taken here as initial ones. Group B is the olivine at 1400°C for 27 hours, and group C is the olivine at 1400°C for 7days. The standard deviation of curvature ($\sigma\kappa$) of each grain is calculated. Using the shapes of group A, we have performed the rounding simulation and obtained the relation between the average standard deviation of curvatures of grains and virtual time. Using this relationship, the average curvature κ of group B and group C were assumed to be corresponding to virtual time of about 0.12 and 0.42 respectively. The real time of group B and C are 27 hours and 7 days. Now we can calculate the value $Dw\gamma$. When Ω is assumed to be 1.2×10^{-23}(cm3), the value is ca. 8×10^{-9} (erg cm s^{-1}).

DISCUSSION: This value is about 1000 times larger than the theoretically estimated value of Ohtani [3] for solid state diffusion. Therefore the rounding rate is also 1000 times faster than his model in micrometer scale. However, the rounding process in cm scale is not more rapid than Ohtani's value, because the rounding time is proportional to the fourth power of the grain size judging from the equation (1), while the time was proportional to the third power of size in Ohtani's model. This result shows the very fast solid-state rounding process for micron sized olivine.

The application of these results to the texture of natural pallasite would require another paper. Here we preliminary use the critical radius (Rc) of olivine grains in natural pallasites. Rc is defined here as the grain size below which most grains become spherical. This critical radius for rounded pallasites is 0.25mm and that for angular pallasites is 10µm. Our experimental and theoretical results suggest that the angular one was produced by ca. five-year heating at 1400°C and the rounded one by ca. $2x10^6$ year-heating at 1400°C.

In order to apply these considerations to the real natural pallasites, the temperature environment should be considered. Natural systems are essentially consisted of Fe-Ni-S and olivines. The eutectic T of Fe-Ni-S system is around 1000°C [7]. Therefore, natural systems include Fe-Ni-S melts above this temperature. Our rounding experiments at different temperatures indicate that the rounding process would require an unrealistic time of over 10^{11} years at 1000°C. The presence of melt film around olivines might enhance greatly the rounding kinetics of the order of 10^5 [5]. Consequently, rounded types of pallasites can be formed in the presence of melts above 1000°C. On the other hand, for angular types of pallasites, the presence of melts and the high temperature condition should be minimum for conserving their angular shapes. Therefore the pallasites might have been mixed at temperatures around 1000°C and cooled down very rapidly at a shallow depth.

Experiments involving a partially molten FeNiS matrix are in progress and will be presented in a subsequent article.

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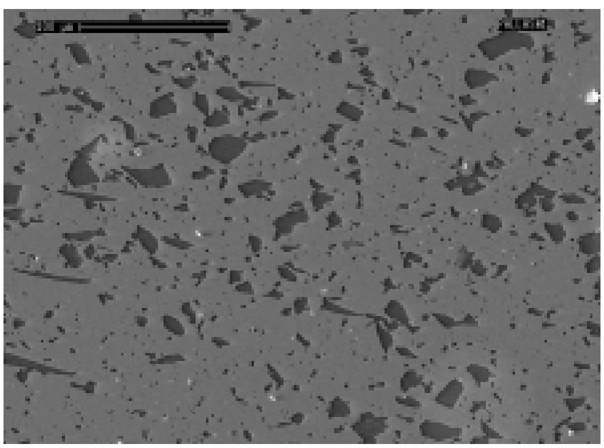

Fig. 1. Secondary electron image of an experimental product at 1400°C for 4 hours. Dark gray grains are olivines and light gray matrix is FeNi metal. Scale is 100 µm.

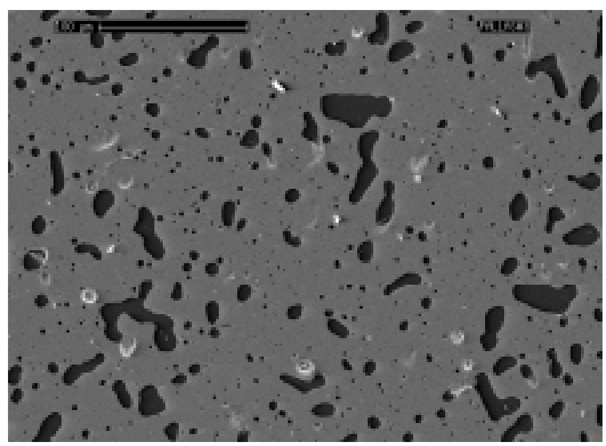

Fig. 2. Secondary electron image of an experimental product at 1400°C for 7 days. Scale is the same as Fig.1.